Recycling deep cratonic lithosphere and generation of intraplate magmatism in the North China Craton

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Abstract

Early Cretaceous alkaline picrites and high-magnesium basalts from the North China craton provide evidence for recycling of continental lithosphere by density foundering. Both the picrites and basalts contain xenocrystic olivines with high $Fo_{92\text{-}93}$ and low CaO (<0.10%), consistent with the lavas' derivation from, or interaction with Archean mantle lithosphere.

Most importantly, both the picritic and basaltic lavas contain unusual, reversely zoned clinopyroxene phenocrysts whose cores have low MgO, high Na_2O (up to 2.4 wt.%, or 17.3 mol%Jd), and frequently contain ilmenite exsolution lamellae, consistent with their crystallization from an eclogite-derived melt (tonalite or trondhjemite). In contrast, the clinopyroxene exteriors have low Na_2O (<0.92 wt.%, or <6.5 mol% Jd) and are lamellae-free, suggesting crystallization from a mantle-derived melt (picrite or basalt). Both the cores and exteriors have high Al_2O_3 contents (up to 6.9 wt.%). These features reflect crystallization of the cpx from an aluminous melt at mantle depths, with the cores forming at a significantly greater depth ($\geq$ 2.5 GPa) than the surrounding cpx ($\geq$ 1.5 GPa). Calculated primary melt compositions further constrain the magmas' formation at 3-4 GPa, in the presence of garnet. The unusually low CaO, high Ni/MgO and low 100Mn/Fe of primary melts indicate derivation of both the picritic and basaltic lavas from pyroxenite sources containing limited or no olivine. High Sr/Y, LaN/YbN and Th/U and low Lu/Hf, together with radiogenic initial $^{87}Sr/^{86}Sr$ and $^{187}Os/^{188}Os$ ratios and negative εNd values implicate contributions from melts derived from foundered eclogitic lower continental crust. Modelling suggests that the basalt source region contained a variable proportion (30-40%) of eclogite-derived component whereas the source of the picrites, on average, likely contained a generally higher proportion (60-70%) of a different eclogite-derived component.

Collectively, these results suggest that both the basaltic and picritic lavas originated by partial melting of Archean lithospheric mantle that was variably hybridised by melts derived from foundered lower crustal eclogite. Together with previous studies, these findings provide new evidence that thinning of the North China craton was caused by the removal of the lower lithosphere (mantle and lower crust). Recycling and melting of eclogitic lower crust may contribute more to mantle heterogeneity than has previously been recognized.

Introduction

Recycling of eclogite of lower continental crust origins, together with the underlying lithospheric mantle, has been proposed to play a role in plume magmatism, crustal evolution and formation of chemical heterogeneities within the mantle (*Arndt & Goldstein*, 1989; *Kay & Kay*, 1991; *Jull & Kelemen*, 2001; *Escrig et al.*, 2004; *Gao et al.*, 2004; *Elkins-Tanton*, 2005; *Lustrino*, 2005; *Anderson*, 2006). Eclogites have lower melting temperatures than mantle peridotites (*Yaxley & Green*, 1998; *Yaxley*, 2000; *Rapp et al.*, 1999; *Kogiso et al.*, 2003; *Sobolev et al.*, 2005, 2007), and as foundered, silica-saturated eclogites heat up, they will produce silicic melts (tonalite to trondhjemite) that may react extensively with overlying mantle peridotite. Such reaction may produce an olivine-free pyroxenite, which, if subsequently melted, will generate basaltic melt (*Kogiso et al.*, 2003; *Sobolev et al.*, 2005, 2007; *Herzberg*, 2006).

Although recycling of eclogite in subducted oceanic lithosphere is a direct consequence of plate tectonics and its consequences for mantle composition have been extensively studied (*e.g.*, Hawaii) (*Hofmann & White*, 1982; *Sobolev et al.*, 2005, 2007; *Herzberg*, 2006), recycling of eclogite formed in deep continental lithosphere is more controversial and only a few studies have considered its effect on the composition of mantle derived magmas (*McKenzie & O'Nions*, 1983; *Arndt & Goldstein*, 1989; *Escrig et al.*, 2004; *Elkins-Tanton*, 2005; *Lustrino*, 2005; *Anderson*, 2006). Here we present petrographic and geochemical evidence that Mesozoic basalts and picrites from the North China craton derive from mantle that was modified by interaction with melts from foundered eclogite.

The North China Craton

The North China craton (NCC; Figure 1) is one of the world's oldest Archean cratons, preserving crustal remnants as old as 3800 Ma (*Liu et al.*, 1992). The NCC is also one of the world's most unusual cratons, as the eastern block was reactivated in the Mesozoic. This portion of the craton had a cold and thick lithosphere, typical of other Archean cratons, at least through the Ordovician, when kimberlites erupted that carried diamonds and refractory garnet peridotites (*Menzies et al.*, 1993; *Griffin et al.*, 1998), the latter of which have Archean Os model ages (*Gao et al.*, 2002; *Wu et al.*, 2006; *Zhang et al.*, 2008).

Reactivation of the craton began in the Early Mesozoic, with uplift and the onset of magmatism, followed by basin development. The magmatism peaked volumetrically in the Late Cretaceous (120-132 Ma; *Wu et al.*, 2005). This early, compositionally diverse magmatism was followed by Cenozoic intraplate basaltic volcanism. Cenozoic basalts in the Eastern Block carry mantle xenoliths that equilibrated to a high geotherm (*Xu*, 2001; *Zheng et al.*, 2006), have a relatively fertile bulk composition (*Menzies et al.*, 1993; *Griffin et al.*, 1998; *Rudnick et al*., 2004) and Os isotopic compositions similar to the modern convective mantle (*Gao et al.*, 2002; *Wu et al.*, 2003, 2006).

The above observations have been used to suggest that ancient, cratonic mantle lithosphere, similar to that present beneath the Kaapvaal, Siberian and other Archean cratons, was removed from the base of the Eastern Block of the NCC during the Mesozoic, and was replaced by younger, less refractory lithospheric mantle. Whether the replacement was caused by foundering, stretching or thermal/chemical erosion of the deep lithosphere due to upwelling asthenosphere is a matter of great debate (*Xu*, 2001; *Gao et al.*, 2004; *Wu et al.*, 2005; *Menzies et al.*, 2007; *Zhang et al.*, 2007; *Huang et al.*, 2007).

Two suites of Early Cretaceous mafic magmas are investigated here: the Sihetun high-Mg basalts (124–125 Ma), which erupted in western Liaoning Province, and the Feixian alkaline picrites (119 Ma), which erupted in western Shandong Province (Figure 1).

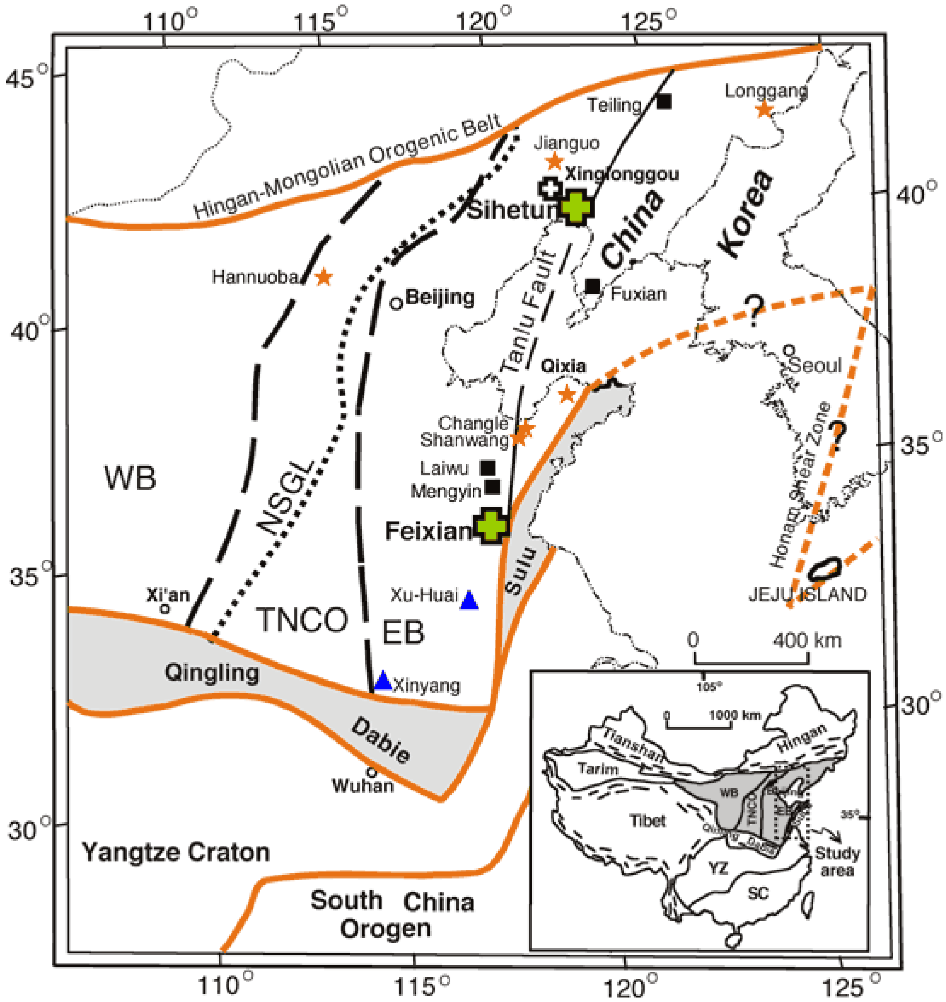

Figure 1: Geologic sketch map of the North China craton (shaded on inset). The two suites of Early Cretaceous lavas under investigation are shown as large filled crosses. Click here for fuller figure caption.

Evidence for recycling deep cratonic lithosphere and generation of intraplate magmatism

Both the picrites and basalts contain xenocrystic olivines with high Fo_{92-93} and low CaO (<0.10%), consistent with the lavas' derivation from, or interaction with, Archean mantle lithosphere (Figure 2). Most importantly, both the picritic and basaltic lavas contain unusual, reversely zoned clinopyroxene phenocrysts whose cores have low MgO, high Na_2O (up to 2.4 wt.%, or 17.3 mol%Jd; Figure 3), and frequently contain ilmenite exsolution lamellae, consistent with their crystallization from an eclogite-derived melt (tonalite or trondhjemite). In contrast, the clinopyroxene exteriors have low Na_2O (<0.92 wt.%, or <6.5 mol% Jd) (Figure 3) and are lamellae-free, suggesting crystallization from a mantle-derived melt (picrite or basalt). Both the cores and exteriors have high Al_2O_3 contents (up to 6.9 wt.%). These features reflect crystallization of the cpx from an aluminous melt at mantle depths, with the cores forming at a significantly greater depth ($\geq$ 2.5 GPa) than the surrounding cpx ($\geq$ 1.5 GPa). Calculated primary melt compositions further constrain the magmas' formation at 3-4 GPa, in the presence of garnet (Figure 4a). The unusually low CaO (Figure 4b), high Ni/MgO and low 100Mn/Fe (Figure 4c) of primary melts indicate derivation of both the picritic and basaltic lavas from pyroxenite sources containing limited or no olivine. High Sr/Y, LaN/YbN and Th/U and low Lu/Hf, together with radiogenic initial $^{87}Sr/^{86}Sr$ and $^{187}Os/^{188}Os$ ratios and negative εNd values implicate contributions from melts derived from foundered eclogitic lower continental crust. Modelling suggests that the basalt source region contained a variable proportion (30-40%) of eclogite-derived component whereas the source of the picrites, on average, likely contained a generally higher proportion (60-70%) of a different eclogite-derived component (Figure 5).

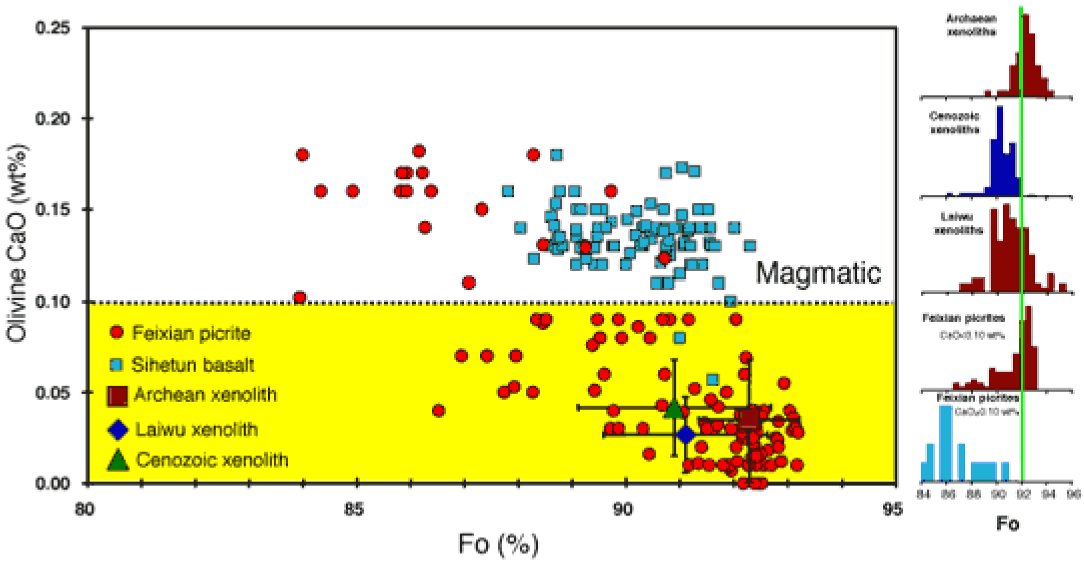

Figure 2: Left: Fo (forsterite = 100Mg/(Mg+Fe), where Mg and Fe represent molar proportions) versus wt.% CaO plot of olivine cores from Early Cretaceous Feixian alkaline picrites and Sihetun high-Mg basalts. Right: Fo histograms show the systematic compositional differences in olivines from different sources. Olivines from the Feixian picrites, with CaO $\geq$ 0.10%, have Fo < 92, consistent with a magmatic origin, whereas those with CaO < 0.10% have Fo >92, consistent with a xenocrystic origin. Click [here](#) or on Figure for enlargement. Click [here](#) for fuller figure caption.

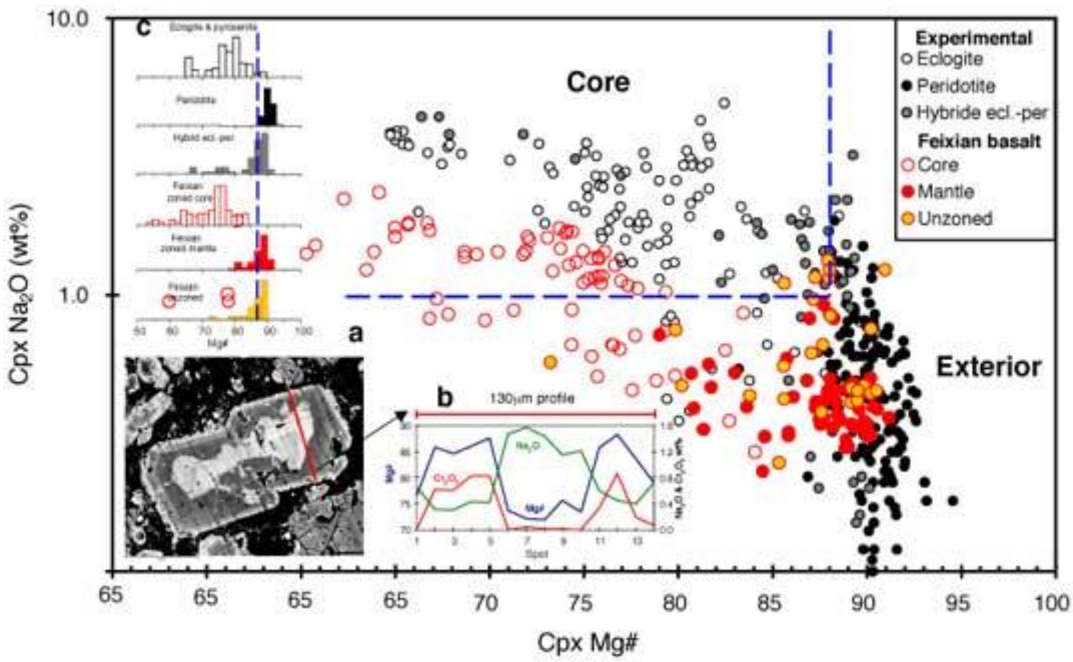

Figure 3: Core-exterior compositions of reversely zoned clinopyroxene phenocrysts from the Feixian alkaline picrites. (a) backscattered electron image (BSE) and (b) compositional profile of a euhedral clinopyroxene phenocryst along [010] plane from sample SFX19. The dark areas are Mg-rich and the light areas are Fe-rich. The main Mg# versus Na_2O plot and (c) Mg# histogram compare experimental clinopyroxenes in equilibrium with melts derived from eclogite (including garnet pyroxenite), peridotite and hybrid eclogite-peridotite. Click [here](#) or on Figure for enlargement. Click [here](#) for fuller figure caption.

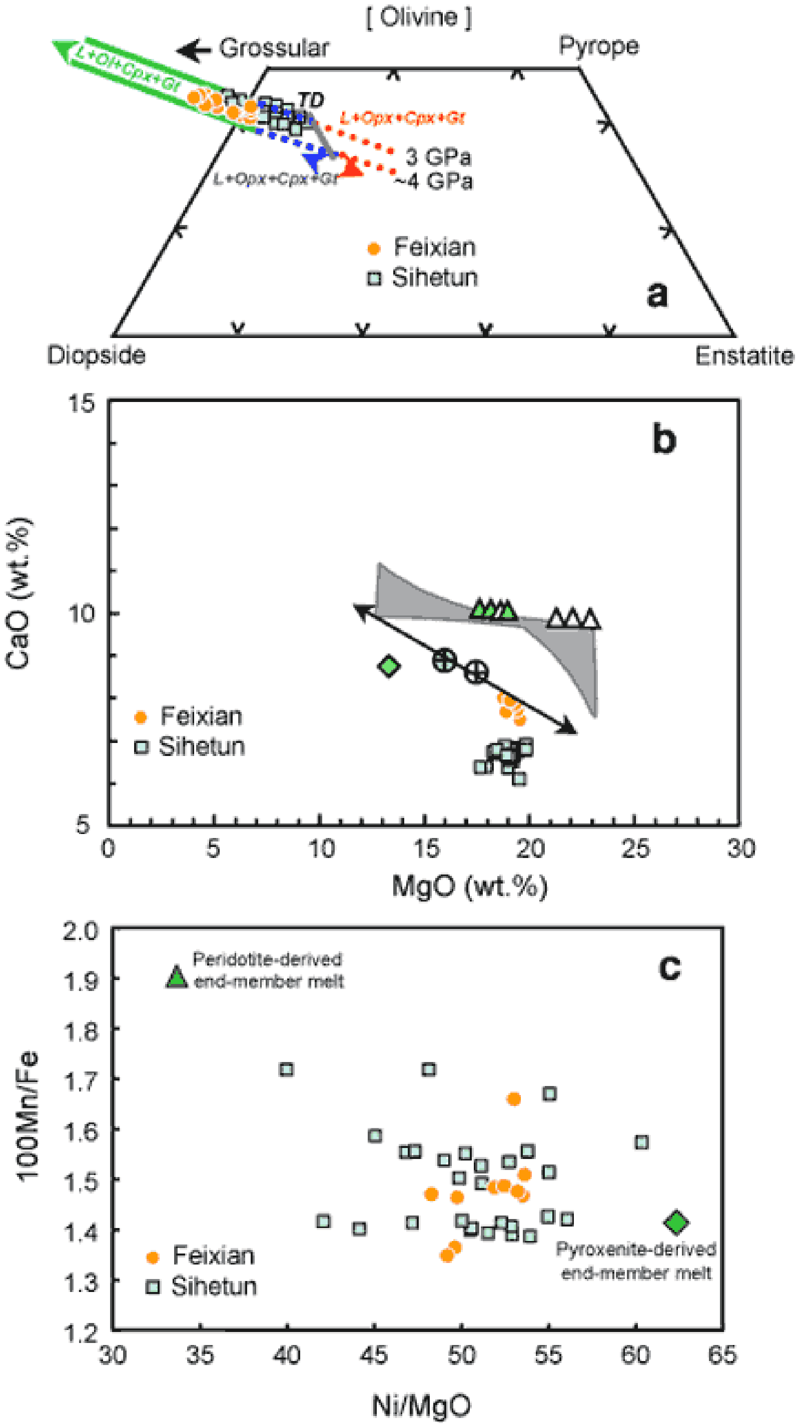

Figure 4: Compositions of primary melts calculated for the Feixian alkaline picrites and Sihetun high-Mg basalts. (a) Mole% projection from or towards olivine into part of the pyroxene-garnet plane compared with cotectics at 3 and 4 GPa (Herzberg, 2006). Thick line labelled "TD" is the thermal divide between olivine-rich and SiO_2-rich sides of the composition space. (b) MgO versus CaO. Filled and open triangles indicate primary melts and solidus melts from peridotites (Herzberg, 2006; Sobolev et al., 2007), while filled diamond represents primary melt from pyroxenite (Sobolev et al., 2007). Shaded area denotes accumulated fractional melt compositions for a pressure range from 3 to 7 GPa (Herzberg, 2006). Filled and open circles with a cross indicate high- and low-SiO_2 Hawaiian parental magmas (Herzberg, 2006). Arrows display the effects of olivine addition (right pointing) and subtraction (left pointing; Herzberg, 2006). (c) Ni/MgO versus 100Mn/Fe ratios of primary melts compared to experimentally produced peridotite and pyroxenite-derived end-member melts [supplementary Table S2 of Sobolev et al. (2007)]. Click here for fuller figure caption.

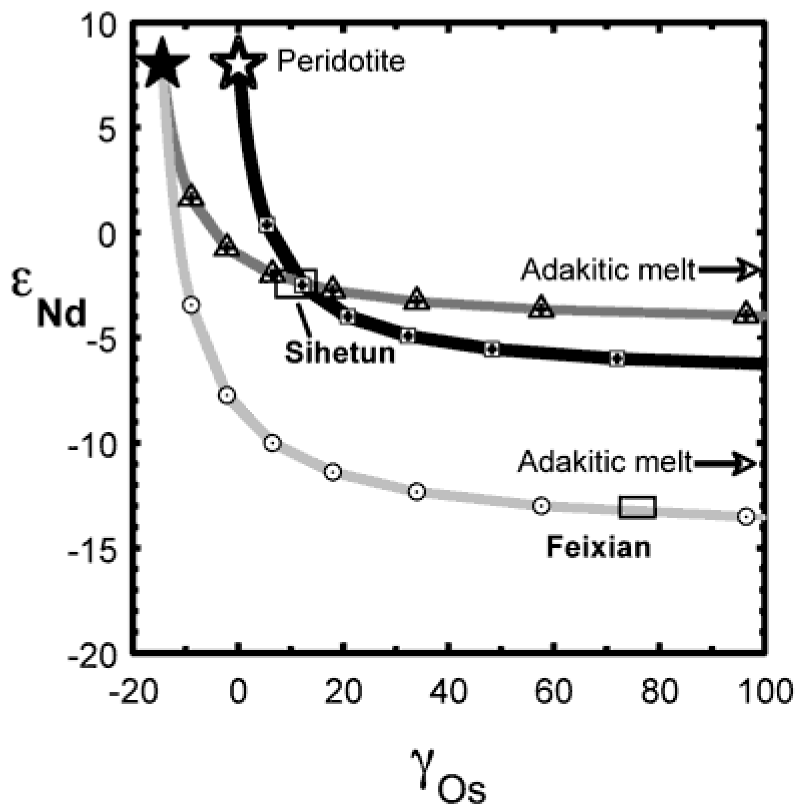

Figure 5: γOs versus εNd mixing diagram for silicic melt-peridotite mixtures as discussed in the text. Starting peridotite compositions are shown as stars. Solid star reflects ancient NCC peridotite. Open star is peridotite with chondritic Os isotopes and the same concentrations and Nd isotopes as ancient peridotite. Starting adakitic melt compositions for the models are beyond the scale of the figure. Triangles, squares and circles show increments of 10% mixing of melt into peridotite. Boxes show estimated compositions of Sihetun basalt and Feixian picrite sources. Click here for fuller figure caption.

Collectively, these results suggest that both the basaltic and picritic lavas originated by partial melting of Archean lithospheric mantle that was variably hybridised by melts derived from foundered lower crustal eclogite. Together with previous studies, these findings provide new evidence that thinning of the North China craton was caused by the removal of the lower lithosphere (mantle and lower crust). They further suggest that recycling and melting of eclogitic lower crust may contribute more to mantle heterogeneity than has previously been recognized.

Acknowledgments

We thank Claude Herzberg for calculation of and constructive discussion on the primary melt compositions and contributing Figure 4a. We thank H.Y. He, G.M. Shu, X.C. Wang, and H. Zhang for help in Ar-Ar dating, electron microprobe, chemical and isotopic analysis, and field work.

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